Transport Theory for Propagation and Reverberation

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LONG-TERM GOALS

Development of computationally efficient modeling methods for shallow water propagation and reverberation that can account for the effects of multiple forward scattering from waveguide boundary roughness and volume heterogeneity such as internal waves.

OBJECTIVES

Previously, our shallow water propagation model based on transport theory was extended to include reverberation, and it was found that sea surface forward scattering could have very important effects on reverberation level at mid frequencies, e.g., at 3 kHz. One objective in FY14 was to utilize reverberation measurements made during TREX13 combined with a detailed environmental characterization to verify through data-model comparisons the importance of sea surface forward scattering on shallow water reverberation level. An additional objective in FY14 was to use transport theory results to support the development of an effective surface reflection loss model that can approximately account for effects of surface forward scattering in ray-based or mode-based propagation and reverberation codes.

APPROACH

Accurate propagation and reverberation modeling is important for many prediction methods that are important for Navy applications and for underwater acoustics systems development. While acoustic propagation and reverberation modeling has been extensively developed for many years, significant limitations still exist on current capability, particularly in the area of computation speed. In addition, the modeling problem increases in complexity as the frequency is raised from the low frequency region (< 1 kHz) to the mid frequency region (1–10 kHz). At mid frequencies (and higher) the effect of forward scattering from the sea surface and bottom has a greater effect on propagation and reverberation than in the low frequency region, especially in shallow water environments.

The available options for modeling forward scattering in propagation are very limited, and are largely confined to computationally intensive methods that can yield benchmark solutions for certain simplified problems. When PE is used for practical propagation modeling, only large-scale bathymetry variations are included with small-scale boundary roughness ignored, and internal waves are also generally ignored. Even the simple expedient of using a loss at the boundary to approximately account for boundary roughness is not conveniently included in PE propagation simulations. Similarly, normal

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mode methods generally ignore mode coupling due to boundary roughness in forward propagation, and in reverberation simulations only a single scattering (the backscattering) is included. In order to include the stochastic effects of boundary forward scattering and internal wave forward scattering in propagation simulations, investigators have typically applied a full-wave method, such as PE, and performed propagation simulations using many realizations of the fluctuating environment in a "Monte Carlo" approach. Averaging the results over the set of realizations can then give accurate results for averages (or moments) of the field, and by using a sufficient number of realizations even pdfs of field amplitudes or intensities can be obtained. In the case of boundary roughness scattering, simulations using the finite element method have also been used. The computational demands for full-wave Monte Carlo simulations for propagation and particularly for reverberation are severe. Instead of doing time consuming Monte Carlo simulations, much faster solutions for field moments can be obtained if equations governing the evolution of the moments themselves can be obtained and solved. Any method that works with evolution equations for the moments of the propagating quantities can be described as a "transport theory," though not always referred to as such.

Therefore, the need exists for much faster computational approaches for obtaining moments of the field for propagation and reverberation at mid frequencies that can account for boundary and internal wave scattering. Our approach is based on expanding the acoustic field in modes, and therefore would most readily apply at mid-frequencies and below, and in relatively shallow water environments such as on the continental shelf.

We have focused on the case where forward scattering is due to scattering from sea surface roughness. Evolution equations are obtained for the first and second moments of the mode amplitudes, accounting for mode coupling due to scattering from a rough sea surface using first-order perturbation theory [1]. Comparisons with rough surface PE simulations [2] have been used to verify the accuracy of the transport theory method for one-way propagation. It should be kept in mind that transport theory is much faster than full wave approaches that use a Monte Carlo method with many rough surface realizations. Also, any number of forward scattering interactions can be accounted for as the field propagates along the waveguide.

While rough surface PE simulations has shown the accuracy of transport theory predictions for average mode amplitude decays in one-way propagation, the effects of sea surface forward scattering on reverberation level has been found to be even more significant than on one-way propagation. Thus, it is important to verify reverberation transport predictions as well. TREX13, a propagation and reverberation experiment carried out near Panama City, Florida in the spring of 2013, was planned to obtain suitable reverberation results to give a diffinitive test of transport theory predictions, since the environment was characterized in sufficient detail to highly constrain reverberation modeling. DJ Tang and Todd Hefner from APL-UW were the co-Chief Scientists for TREX13.

Because transports theory has shown the importance of accounting for sea surface forward scattering in accurately modeling shallow water reverberation at mid frequencies, it becomes imperative to develop as approximate way to include these effects into traditional ray-based or mode-based reverberation codes. A separate project supported by PMW-120 (M. Speckhahn) has been ongoing with this particular goal in mind. The effect of surface forward scattering is treated with an effective surface reflection loss model for the total field (referred to as TOTLOS), where the total field is the combination of the coherent (or reflected) component, and the incoherent (or scattered) component. The original approach in developing TOTLOS was to base it on the results of Monte Carlo rough surface PE results, but as transport theory became available it became clear that results from it were

much more suitable to support TOTLOS development. As a result TOTLOS development has become an important secondary goal of the present project.

The approach being used in the development of TOTLOS will be summarized briefly. Because our transport theory is mode-based, it readily provides mode amplitudes as a function of range for any particular shallow water environment of interest. Each mode amplitude can be associated with a particular grazing angle at the sea surface. The decay of each mode amplitude over a cycle distance (the distance between surface interactions assuming reflected rays) is first determined, and the contribution of loss at the bottom is removed. What remains is identified as a loss in a single surface interaction, and in many cases that loss is negative, which means that there is a gain. In such a case more energy is being forward scattered into a particular mode than is being lost into the bottom in one cycle distance. With this information determined as a function of range for each mode, it is possible to form an effective reflection loss (the TOTLOS model) that will replicate the transport theory results for propagation when surface forward scattering occurs. The model can then be tested in reverberation geometries using TOTLOS in a ray-based code such as CASS-GRAB and making comparisons with transport theory reverberation results.

The TOTLOS model depends not only on the sea surface roughness and frequency, but on range and on the water column and bottom properties, i.e., the TOTLOS model is scenario dependent. To avoid the need to tune the model to each scenario with appropriate transport runs, the approach is to develop an algorithm using quasi-analytic expressions for the model parameters based on a selection of transport runs, and then use that algorithm to define the parameters for the model in general.

The key individuals assisting with the transport theory work are Frank Henyey, Jie Yang, and Tim Elam, all at APL-UW. Todd Hefner, also at APL-UW, has been assisting with TOTLOS model development.

WORK COMPLETED

The goal has been to examine the effect forward scattering from sea surface roughness on reverberation, which is dominated by bistatic backscattering from the bottom. Data-model comparisons have been made for selected reverberation data sets obtained during TREX13 with this goal in mind. The data sets were selected through analysis by Jie Yang to minimize the contributions to reverberation from scattering by schools of fish.

The transport code was modified to accept 1-D surface roughness spectra obtained from 2-D roughness spectra measured with a wave buoy. The analysis of the wave buoy data was performed by Peter Dahl and David Dall'Osto (both at APL-UW), who also provided the 1-D roughness spectra along the direction associated with the reverberation measured with a horizontal line array. The 1-D roughness spectra are the marginal spectra obtained by integrating over the wave number content orthogonal to the direction along the reverberation track. The reduction of a 2-D spectrum to a 1-D spectrum is not unique, and this is just one method for making that reduction. This point will be discussed further in the section on results.

Transport propagation and reverberation results have also continued to support development of the more approximate TOTLOS surface loss model to allow the effects of surface forward scattering to be incorporated into standard ray-based models for propagation or reverberation such as CASS-GRAB or mode models for similar applications. During FY14 the TOTLOS model has been generalized to

account for a range of sediment sound speeds, in addition to a range of frequencies, wind speeds, and water depths, all for the restricted case of an isovelocity sound speed profile and for a surface roughness model based on an isotropic Pierson-Moskowitz spectrum.

RESULTS

One important prediction from transport theory modeling is that at mid frequencies the reverberation level will decrease as the sea state rises, even when the bottom reverberation dominates. In order to see what is at stake, the magnitude of this effect is illustrated in Figure 1, reproduced from the FY12 and FY13 reports. For this example the frequency is 3 kHz, the rough sea surface is modeled with an isotropic Pierson-Moskowitz roughness spectrum for a wind speed of 7.7 m/s giving an rms wave height of 0.31 m, the sound speed is taken as isovelocity at 1500 m/s over a water depth of 50 m, and the bottom roughness is described by the Reverberation Modeling Workshop "typical roughness" model [3].
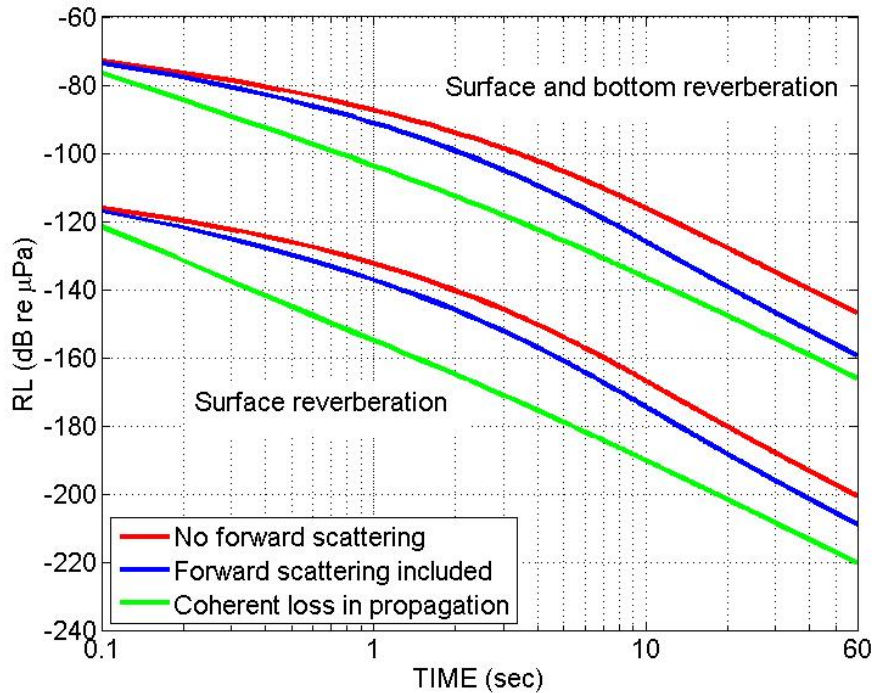

Figure 1. Reverberation predictions at 3 kHz obtained with transport theory. The red curves ignore all effects of boundary roughness during propagation. The blue curves account for surface forward scattering. The green curves approximate the effect of surface forward scattering in terms of a coherent loss.

For the top set of curves in Figure 1, bottom reverberation dominates, the red curve is a prediction corresponding to a very low sea state, while the blue curve is the transport theory result that fully accounts for the effects of surface forward scattering. The green curve is the result if a coherent loss is used to model the surface interaction for the two-way propagation. The reverberation levels can be considered relative levels, since a typical source level has not been included. Both options of no forward scattering or the use of a coherent loss can be readily applied, for example, to ray-based reverberation modeling, but modeling error on the order of 10 dB is indicated for either option.

Therefore is quite important to verify the accuracy of the transport theory prediction by making data/model comparisons with TREX13 results. While the sea state assumed for Figure 1 is modest by ocean standards, even it is beyond what could be attained during TREX13, since the R/V Sharp was forced to come out of its four-point moor when the sea state approached the level assumed for Figure 1, and thus reverberation data could not be obtained for an rms surface height as great as 0.31 m. Therefore the differences between the three ways of modeling the reverberation shown in Figure 1 are less for the TREX data sets, but the important thing is to verify the accuracy of the transport theory predictions for the conditions that were accessible. And, from Figure 1 it can be assumed that bottom reverberation will dominate over surface reverberation for the TREX reverberation data sets.

The original expectation was that the TREX13 environment would be relatively benign, reducing the complexity of the environmental characterization task. The receiving horizontal array provided an angular width of 2.2 degrees, yielding a confined region along the bottom that contributed to the reverberation along a track roughly parallel to shore, and therefore at approximately a constant depth of about 19 m. Figure 2 shows the results from Chris de Moustier of a 400 kHz multibeam survey of the bottom in the vicinity of the reverberation track, which lies along a narrow band including the blue triangles (vertical array locations for propagation measurements). The reverberation source and horizontal receiving line array were located close to the R/V Sharp at the upper left end of the rectangular surveyed region. The brightness within the rectangle represents the relative backscattering level at 400 kHz.

Figure 2. Multibeam survey map of the region containing the main TREX13 reverberation track showing ridge and swale structure

As can be seen from Figure 2, the sea bottom along the reverberation track consists of a ridge and swale structure. The depth variation is minor along the track, but near the center of the deeper regions (the swales) is a region of mud. And contrary to expectations, the reverberation level has peaks correlating to the locations of the mud regions, suggesting that there may be localized scatterers such as clumps of shells or sand embedded within the mud. This finding complicates the goal of doing fully constrained modeling of the reverberaion level.

Figure 3 showed the measured reverberation level on three different days during TREX13 when returns from fish schools were negligible. The bearing of 129 deg corresponds to steering the receiving array to obtain reverberation from the standard reverberation track as indicated in Figure 2. The reverberation data designated R17 were obained on April 24, 3013 during a period with a very low sea state, generally considered a "calm day." The wave buoy data give an rms wave height of 0.0526 m, and the reverberation results should not differ greatly from a modeling result when no forward scattering is included. The reverberation data designated R53 were obtained on May 1, 2013, during a period of modest wind and waves traveling approximately along the reverberation track from the southeast toward the northwest. The wave buoy data give an rms wave height of 0.128 m. Transport theory models the propagation in 2-D (range and depth), and this case should correspond closely to the 2-D assumptions inherent in that modeling. The reverberation data designated R61 were obtained on May 7, 2013 shortly after the R/V Sharp returned to the experiment site after a weather event forced it to leave the site and stay several days in port. The wave buoy data give an rms wave height of 0.241 m, but the wave direction was almost perpendicular to the reverberation track, making it less clear that modeling forward scattering for propagation along the track with a 2-D model will be as accurate.
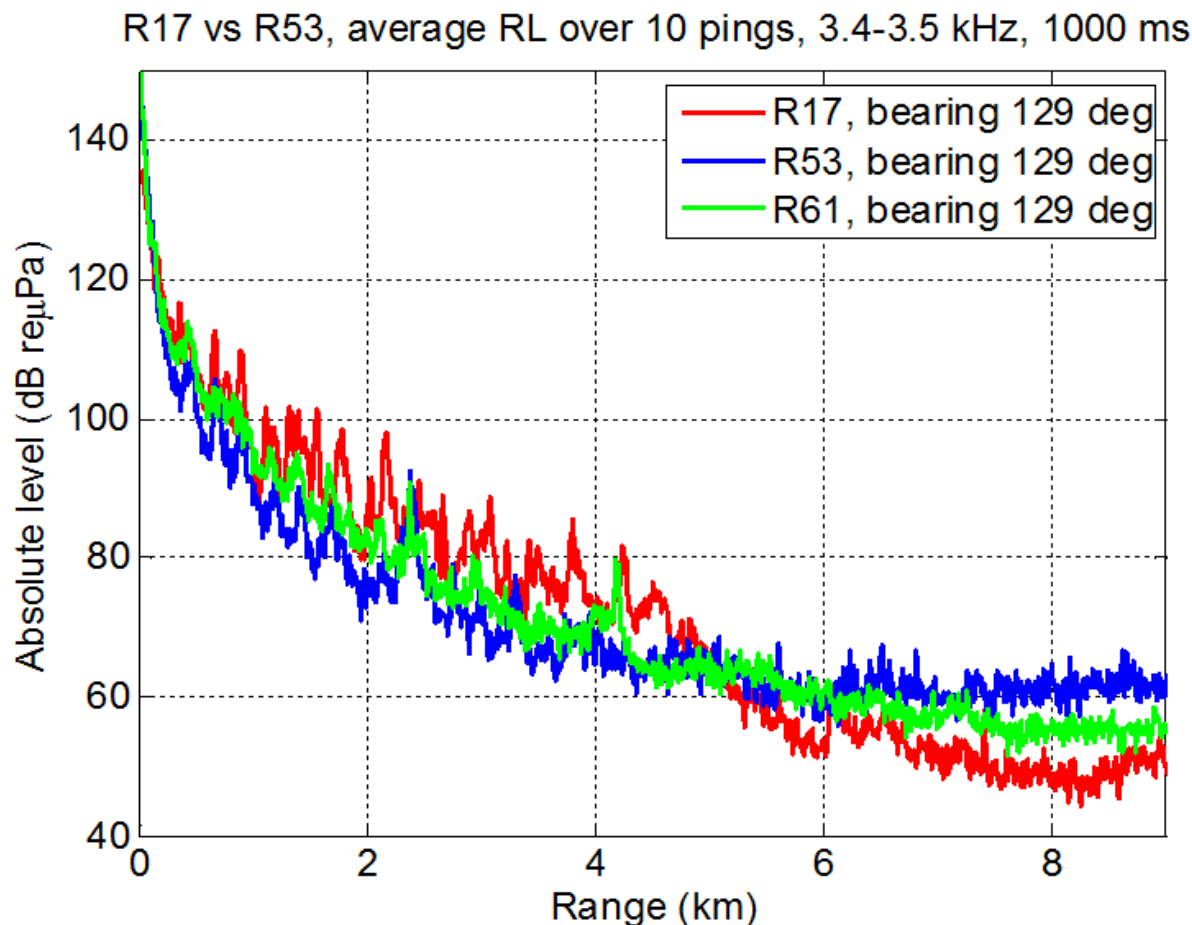

Figure 3. TREX13 reverberation data for April 24 (red), May 1 (blue) and May 7 (green).

The reverberation levels shown in Figure 3 are given as a function of range, where the main bottom scattering occurred, instead of as a function of time. This format makes it easier to correlate changes in the reverberation level with features on the bottom. In particular, the largest spikes in the data,

especially noticeable in the data for April 24 (red curve), are correlated with the locations of the mud regions and are not simply statistical fluctuations. At the present time, a scattering model appropriate for the mud regions is not available, and thus only scattering from roughness at the water-sand interface is being used to model the reverberation. Therefore, an ideal model result should lie along the lower part of the data curves. Note also that the data curves tend to flatten out starting at a range of about 5 km; this is the range at which the reverberation signals begin to merge into the background noise.

It is evident from Figure 3 that the reverberation from the bottom is affected by the sea state, since the same track along the bottom occurs for each day. The reverberation for the relatively calm day (red curve) does have the highest level, in agreement with expectations. Then for May 1 (blue curve) when the rms wave height increased to 0.128 m, the reverberation level was noticeably lower. Finally for May 7 (green curve) when the rms wave height was higher yet at 0.241 m, the reverberation level was not lower than for the May 1 data, but intermediate between the calm conditions of April 24 and the May 1 data. However, the wave direction on May 7 was nearly perpendicular to the reverberation track, which no doubt had some effect on how the forward scattering affected the reverberation level.

In order to model the reverberation from the bottom, a scattering model for the bottom is required. Bottom roughness measurements were made during TREX13 with a laser line scanner and analyzed by Todd Hefner at APL-UW to obtain a roughness spectrum model that was use to obtain the bottom reverberation combined with transport theory for the propagation out and back from the scattering area. Direct path backscattering measurements were also made during TREX13 that can be used to confirm the scattering model based on the roughness measurements, but this analysis has not been completed. Therefore, the bottom scattering model must be considered preliminary at this point.

Figure 4 shows a data-model comparison for April 24, a relatively calm day. As expected, there is essentially no difference between the results treating the sea surface as perfectly flat (light blue curve) and using the measured surface roughess spectrum for that day (red curve). The two curves overlap and appear as an intermediate color. Using the transport theory result for the first moment, which is equivalent to assuming the surface interaction is modeled with a coherent loss, leads to a slightly lower reverberation prediction. The predicted reverberation level for the primary result (red curve) does run along the very bottom envelope of the data, and if anything is lower than ideal agreement. Recall that the upward reverberation spikes are mainly due to enhanced scattering from mud regions and are not being modeled at present. The somewhat low model result, particularly over the first kilometer, may indicate inaccuracy in the preliminary bottom scattering model being used.

The drop of measured reverberation level beginning at a range of about 5 km apparently arose from a subtle change in bottom properties in that region. After the higher sea state that occurred between May 1 and May 7, reverberation data were obtained on another relatively calm day (May 10). As shown in Figure 5, the bottom properties beyond 5 km had apparently been affected in some way by the higher sea state, and the drop in reverberation level in that region no longer occurred.

Figure 6 gives a data-model comparison for a case with a modest sea state giving an rms wave height of 0.128 m with the wave field moving along the reverberation track from the southeast toward the northwest. The difference between the three ways of treating the forward scatter surface interaction is now more noticeable, but still only modest in size.
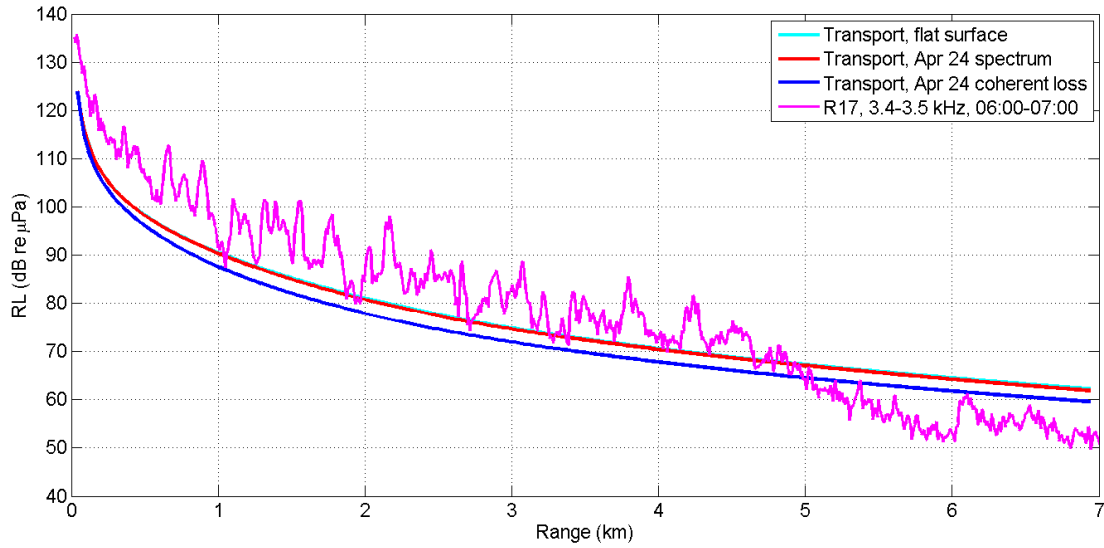
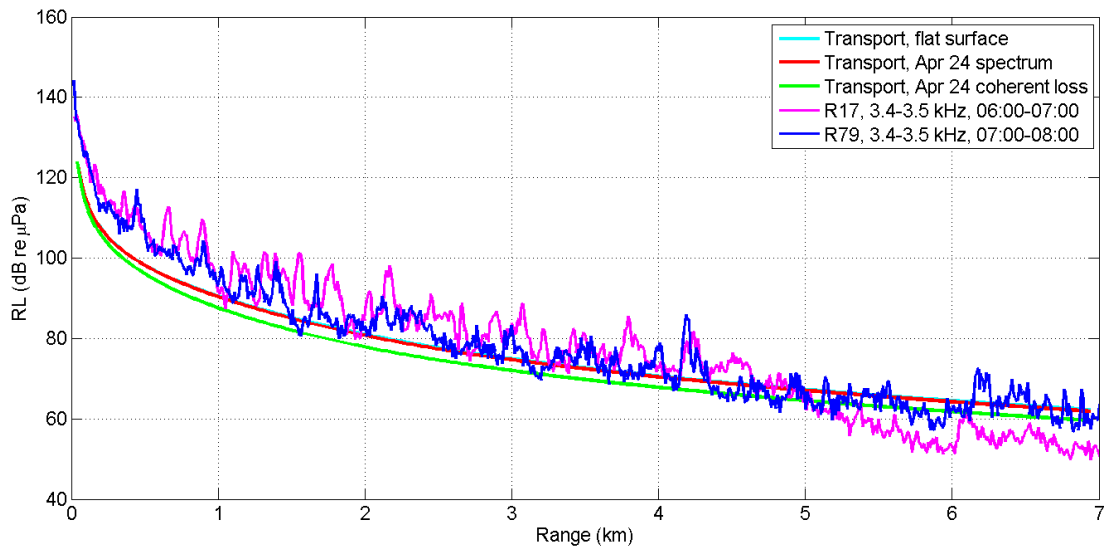***Figure 4. Reverberation data-model comparison for April 24, a relatively calm day.***

Figure 5. Reverberation data-model comparison from Figure 4 with data from a second relatively calm day (May 10) added (R79, dark blue curve).

Figure 7 gives a data-model comparison for a case with a somewhat higher sea state giving an rms wave height of 0.241 m and with the wave field moving approximately perpendicular to the reverberation track. In this case the coherent surface loss treatment gives a result that is clearly too low in comparison with the data. The transport theory result based on the measured spectrum is in reasonable agreement with the data at longer ranges, but underpredicts the data at short ranges. Some of this discrepancy may well be due to three-dimensional effects that are not adequately taken into account using the marginal spectrum to obtain a 1-D surface roughness spectrum for transport theory propagation.
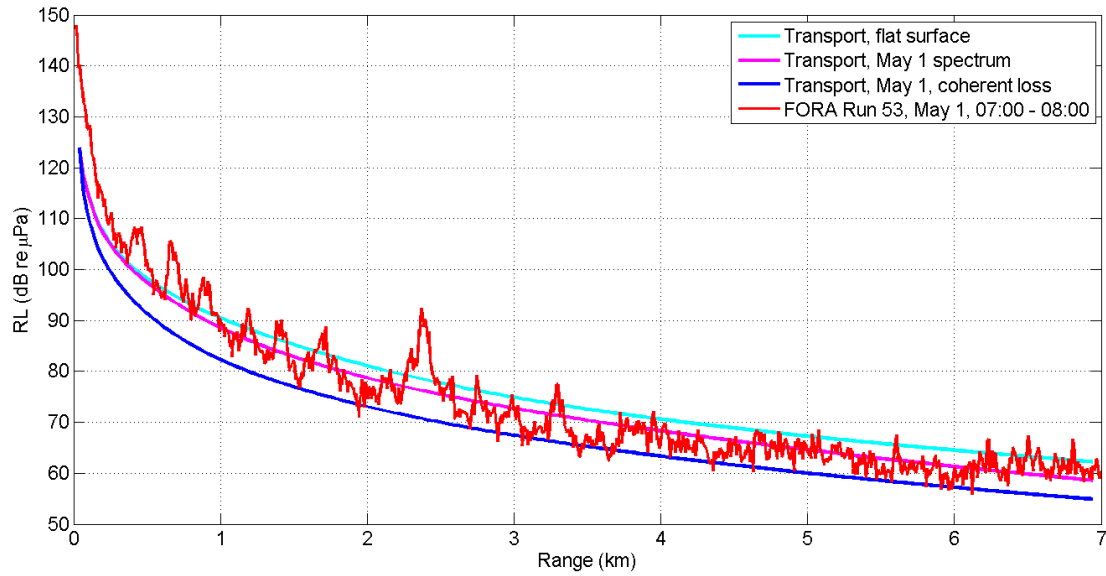
Figure 6. Data-model comparison for May 1 at 3.4-3.5 kHz. The wave direction was approximately parallel to the reverberation track.
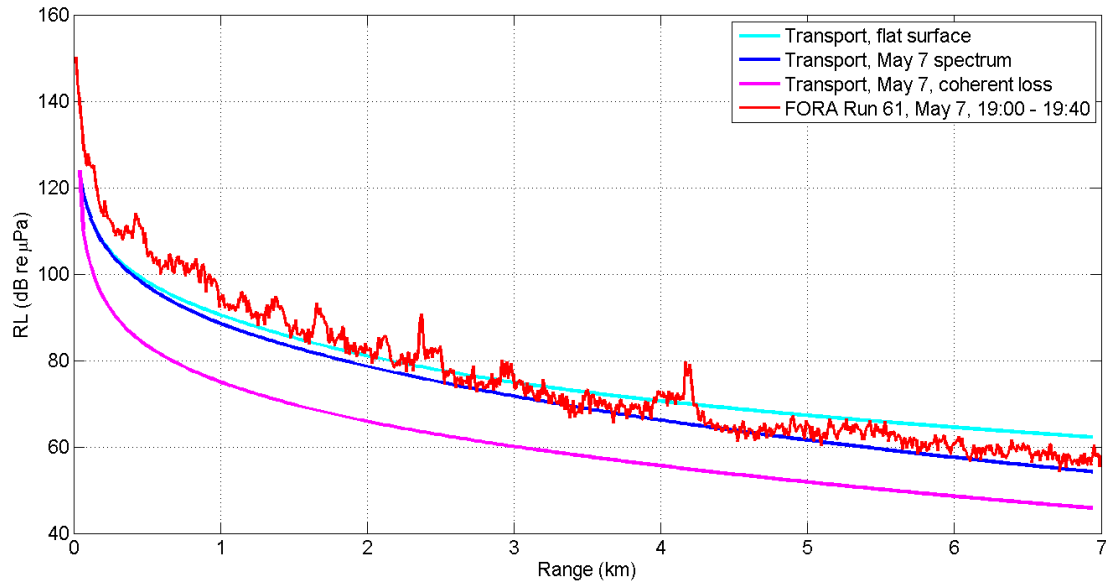

Figure 7. Data-model comparison for May 7 at 3.4-3.5 kHz. The wave direction was approximately perpendicular to the reverberation track.

In summary, surface forward scattering effects are evident in the measured reverberation, as shown in Figure 3. Enhanced scattering from mud regions leads to spikes in the reverberation, complicating detailed data-model comparisons. Further work is needed to refine the bottom scattering model based on direct path bottom scattering measurements to better constrain that aspect of the environment. Further work is also needed to better understand how best to represent the important 2-D aspects of the roughness spectrum with an effective 1-D spectrum for use in propagation and reverberation modeling

that includes surface forward scattering. Nevertheless, the results so far are sufficiently encouraging to indicate that the rather large effects of surface forward scattering shown in Figure 1 for higher sea states than encountered during TREX13 whould be found if data were obtained for such conditions.

IMPACT/APPLICATIONS

Work in transport theory propagation and reverberation modeling should lead to improved simulation capability for shallow water propagation and reverberation in which multiple scattering from rough boundaries is properly taken into account. This capability should be particularly important in the mid-frequency range where multiple scattering effects can be important, yet where a modal description can be used. Transport theory propagation and reverberation modeling has the potential to be even faster than ray tracing, yet be able to account for scattering effects outside the scope of other efficient modeling methods.

RELATED PROJECTS

1. PMW-120 (Marcus Speckhahn) is supporting work on developing a model (TOTLOS) that can approximately account for effects of surface forward scattering in ray-based (such as CASS/GRAB) or mode-based propagation and reverberation models. Results for transport theory are now being used to aid in TOTLOS development, which has become an important component of the present project.

2. The ONR OA project "Mid-Frequency Reverberation Measurements with Full Companion Environmental Support, DJ Tang (PI) is the parent project for TREX13, in which reverberation data have been obtained for verifying the accuracy of transport theory predictions for reverberation.

REFERENCES

[1] E. I. Thorsos, F. S. Henyey, W. T. Elam, B. T. Hefner, S. A. Reynolds, and J. Yang, "Transport theory for shallow water propagation with rough boundaries," *Shallow-Water Acoustics*, Proceedings of the Second International Shallow-Water Acoustics Conference, Shanghai, China, September 16-20, 2009, AIP Conference Proceedings 1272, pp. 99-105.

[2] A. P. Rosenberg, "A new rough surface parabolic equation program for computing low-frequency acoustic forward scattering from the ocean surface," *J. Acoust. Soc. Am.* **105**, 144-153 (1999).

[3] ftp://ftp.ccs.nrl.navy.mil/pub/ram/RevModWkshp_II.

PUBLICATIONS

D. Zou, K. L. Williams, and E. I. Thorsos, "The influence of temperature on the acoustic sound speed and attenuation of seafloor sand sediment," IEEE-JOE (in press).